



**University of  
Zurich**<sup>UZH</sup>

**Zurich Open Repository and  
Archive**

University of Zurich  
University Library  
Strickhofstrasse 39  
CH-8057 Zurich  
[www.zora.uzh.ch](http://www.zora.uzh.ch)

---

Year: 2006

---

## **Three-dimensional forest canopy structure from terrestrial laser scanning**

Danson, F Mark ; Hetherington, David ; Morsdorf, Felix ; Koetz, Benjamin ; Allgöwer, Britta

**Abstract:** A terrestrial laser scanner was used to measure the three-dimensional structure of forest stands in the Swiss National Park, eastern Switzerland. Spatially coincident hemispherical photographs were taken at each sampling point and the position of each point was determined using differential GPS. A scanner model was derived in order to determine the expected number of laser shots in all directions, and these data were compared with the measured number of laser hits to determine directional gap fraction at nine sampling points. Directional gap fraction distributions were determined from the digital hemispherical photography and compared with distributions computed from the laser scanner data. The results showed that the measured directional gap fraction distributions were similar for both hemispherical photography and terrestrial laser scanner data with a high degree of precision in the area of overlap of orthogonal laser scans. Unlike hemispherical photography the laser scanner data offer semi-automatic measurement of gap fraction distributions, plus additional three-dimensional information about tree height, gap size distributions and foliage distributions.

Posted at the Zurich Open Repository and Archive, University of Zurich

ZORA URL: <https://doi.org/10.5167/uzh-77859>

Conference or Workshop Item

Published Version

Originally published at:

Danson, F Mark; Hetherington, David; Morsdorf, Felix; Koetz, Benjamin; Allgöwer, Britta (2006). Three-dimensional forest canopy structure from terrestrial laser scanning. In: International Workshop 3D Remote Sensing in Forestry, Wien (A), 14 February 2006 - 15 February 2006. Institute of Surveying, Remote Sensing and Land Information University of Natural Resources and Applied Life Sciences (BOKU), 50-54.

## THREE-DIMENSIONAL FOREST CANOPY STRUCTURE FROM TERRESTRIAL LASER SCANNING

*F. Mark Danson<sup>1</sup>, David Hetherington<sup>1</sup>, Felix Morsdorf<sup>2</sup>, Benjamin Koetz<sup>2</sup> & Britta Allgöwer<sup>2</sup>*

<sup>1</sup> Centre for Environmental Systems Research, University of Salford, Manchester M5 4WT, UK  
f.m.danson@salford.ac.uk

<sup>2</sup> Department of Geography, University of Zurich, Zurich, Switzerland

### ABSTRACT

A terrestrial laser scanner was used to measure the three-dimensional structure of forest stands in the Swiss National Park, eastern Switzerland. Spatially coincident hemispherical photographs were taken at each sampling point and the position of each point was determined using differential GPS. A scanner model was derived in order to determine the expected number of laser shots in all directions, and these data were compared with the measured number of laser hits to determine directional gap fraction at nine sampling points. Directional gap fraction distributions were determined from the digital hemispherical photography and compared with distributions computed from the laser scanner data. The results showed that the measured directional gap fraction distributions were similar for both hemispherical photography and terrestrial laser scanner data with a high degree of precision in the area of overlap of orthogonal laser scans. Unlike hemispherical photography the laser scanner data offer semi-automatic measurement of gap fraction distributions, plus additional three-dimensional information about tree height, gap size distributions and foliage distributions.

**Keywords:** Terrestrial laser scanner, three-dimensional, forest structure

## 6 INTRODUCTION

The three-dimensional (3d) arrangement of forest canopy elements controls light interception, CO<sub>2</sub> fluxes and canopy hydrometeorological characteristics. Conventional methods of measuring plant canopy structure are time-consuming, labour intensive and error-prone. Direct methods normally involve destructive sampling of canopy elements and in large complex forest or woodland canopies it may be impossible to collect sufficient samples to accurately characterize the structure (Jonckheere et al. 2004). Indirect methods of measuring canopy structure include both light interception instrumentation and hemispherical photography and there is an extensive literature showing how these methods may be used to measure forest leaf area index (LAI), canopy cover, gap size distributions and light climate (Weiss et al. 2004).

Terrestrial laser scanning (TLS) uses range-finding measurement technologies to derive the 3d position of objects within the scanner field of view. TLS are now capable of collecting 3d data clouds (x,y,z, intensity) of several million data points in less than five minutes. Their application in surveying and engineering is now well established and recent research has examined their application for 3d mapping in the environmental sciences (eg. Heritage and Hetherington 2005). Applications of terrestrial laser scanning in forestry have focussed on the rapid semi-automatic determination of stand characteristics like tree density, height and girth, and there now appears to be great potential for the application of TLS in forest inventory and monitoring (Thies et al. 2004, Hopkinson et al. 2004, Watt and Donoghue 2005). However this paper assesses the potential of TLS for measuring the 3d characteristics of forest canopies and specifically the extraction of canopy gap fraction measurements. Well established methods to measure plant canopy structure, based on the point-quadrat methods of Warren-Wilson (1963), have been adapted to use hemispherical photography below forest canopies in order to measure canopy structure. This paper compares hemispherical photography and TLS measurements to derive forest canopy gap fraction, and other stand attributes.

## 7 LASER SCANNER CHARACTERISTICS AND DATA PROCESSING

The laser scanner used in this research was a Riegl LMZ210i which uses a two-axis beam scanning mechanism and a pulsed time-of-flight laser rangefinder measure the 3d position of points within a range of about 350m. Line scan measurements are produced through the rotation of a rotating polygon-mirror and frame scan measurements through the rotation of the optical head of the scanner. The angular step width in both line and frame scan directions may be set by the user to determine the angular separation between laser shots. The line and frame scan angle ranges may also be determined by the user within the limits of the instrument (table 1).

*Table 1: Terrestrial laser scanner characteristics*

Riegl LMZ 210i	
Two-axis beam scanning mechanism	
Single shot time of flight measurement	
Wavelength	900nm
Range (typical)	350m
Line scan angle range	0 – 80o
Frame scan angle range	0 – 333o
Laser beam divergence	3 mrad
Angular step width	0.072 - 0.36o
Measurement resolution (one shot)	25mm
Pulse repetition rate (maximum)	28,000 Hz
Measurement time (typical)	3 mins for 1 million points

Since the TLS used does not record laser ‘misses’, it was necessary to develop a laser scanner model to determine the total number of ‘shots’ per scan, which is dependent on resolution, and line and frame scan angle range. This involved five steps: Cartesian to cylindrical coordinate transform, cylindrical to spherical transform with fixed value of sphere radius (r), spherical to Cartesian transform, deletion of shots in segments at angles greater than or less than the specified line scan angle range. To test the scanner model a single scan was performed using the TLS indoors in an enclosed room with no windows with the scanner pointing towards the ceiling, a line scan angle range of 51.27 to 127.32 ° and frame scan angle range of 0 to 180 °, and a resolution in both directions of 0.18 °. The frequency of laser shots in 5 ° elevation bands from 0 to 90 ° was calculated using both measured and modelled scanner data in spherical coordinates. The results showed very strong agreement between the measured and modelled frequencies giving high confidence in the validity of the scanner model.

## 8 METHODS

Spatially and temporally coincident TLS data digital hemispherical photographs were collected in a semi-natural forest area in the Swiss National Park, Switzerland, in August 2005. The forest is located in the Ofenpass valley at an altitude of approximately 1900m. The dominant tree species is mountain pine (*Pinus mugo*) and some stone pine (*Pinus cembra*). A 300m transect with nine sampling locations was employed. At each sampling point a surveying tripod was levelled and differential GPS data were collected to determine the geographic location of the sampling point. A single hemispherical photograph was taken using an upward looking Nikon Coolpix 4500 with a calibrated hemispherical lens. The hemispherical photographs were analyzed using the Gap Light Analyzer (GLA) software (Frazer et al. 1997). Gap fractions were computed for zenith angles from 0 to 90o with 5o spacing, and averaged over all azimuth angles. LAI was computed for each photograph using the GLA software.

The TLS was then mounted on the tripod at an inclination angle of  $90^\circ$  and a single scan recorded with a line scan angle of approximately  $80^\circ$  and a frame scan angle of  $180^\circ$  (figure 1). The TLS was then rotated through  $90^\circ$  and a second orthogonal scan recorded. The resolution of all scans was set at  $0.108^\circ$  in line and frame scan directions. A single scan recorded about one million points in around four minutes. The scanner data were converted to Cartesian coordinates using the RiScanPro™ software, which included a correction for an angle-dependent shift in the origin of the laser measurements.



Figure 1. Terrestrial laser scanner deployed in Swiss National Park. Orientation of scanner to facilitate upward-looking scanning

## 9 RESULTS

The laser scanner recorded the x,y,z position of all laser hits, plus the intensity of the return and colour information in an RGB file. Only the x,y,z position data are considered in this paper, although it is clear that the intensity data contained useful information on target reflectivity related to target type (figure 2a). Nine sampling locations were used but data for a sub-set of these is presented here. Overall the information content of the laser scans appeared to be similar to that of the hemispherical photographs (figure 2b) but additional range-related data could be easily extracted from the scans. For example the frequency of returns in the z-direction provided data on the vertical distribution of vegetation elements and height of the canopy and xy slices could be used to estimate canopy cover

After conversion to spherical coordinates (figure 2c), the measured scans were compared with the equivalent model scan in order to determine the angular gap fraction distribution. In contrast to the results of Lovell et al. (2003) who found that laser scanning overestimated gap fraction in a pine forest, the distributions derived from laser scanning in our work were very similar to those derived from the hemispherical photography and two contrasting examples are shown in figure 3. Canopy cover estimated from the hemispherical photograph, using only azimuth angles between  $0$  and  $10^\circ$ , for the site in figure 3a was 75.2% and using the ratio of laser shots to hits, over the same range of angles, cover was 75.6%. For the site in figure 3b the same figures were 10.8% and 14.3%.

The orthogonal laser scans sampled the same area of the canopy between zenith angles of  $0$  and  $40^\circ$  (since the line scan angle range was about  $80^\circ$ ) and so provide an independent test of the precision of the laser scanner measurements. In all plots the difference between the gap fraction measurements for the two laser scans was generally small up to  $40^\circ$ . At zenith angles greater than  $40^\circ$  there was some divergence in the gap fraction measured reflecting azimuthal variation in canopy structure. Only a small segment of the hemisphere was not measured and averaging the two orthogonal scans would be a reasonable way to represent the complete gap fraction distribution.

Comparison between the gap fractions determined from the hemispherical photography and from the laser scanner showed general agreement. For the site shown in figure 3a there were some differences at zenith angles between  $20$ - $25^\circ$ , with the hemispherical photography indicating a gap fraction of 40% and the laser scanner 20%. These differences may be due to the solar glare seen in the photograph, or errors related to the manual thresholding of the digital imagery. Alternatively there may be errors in the laser scanner data with underestimation of vegetation cover due to the fine structure of the tree needles and shoots in the canopy. However, the similarity of the data from the two orthogonal scans of the TLS does indicate consistency in the measurements and there is no general

evidence of underestimation of vegetation cover with the TLS. In the example shown in figure 3b the fit between the photography and TLS data is closer but at zenith angles above 40° the laser data appear to show higher gap fraction than the photography which shows zero gap from 60° zenith and above. This is a feature of data from most of the nine plots sampled and suggests that the laser scanner is either measuring small gaps not detected by the photography, or that the laser shots are hitting low reflectance target at far range so that the return intensities are too low for detection.

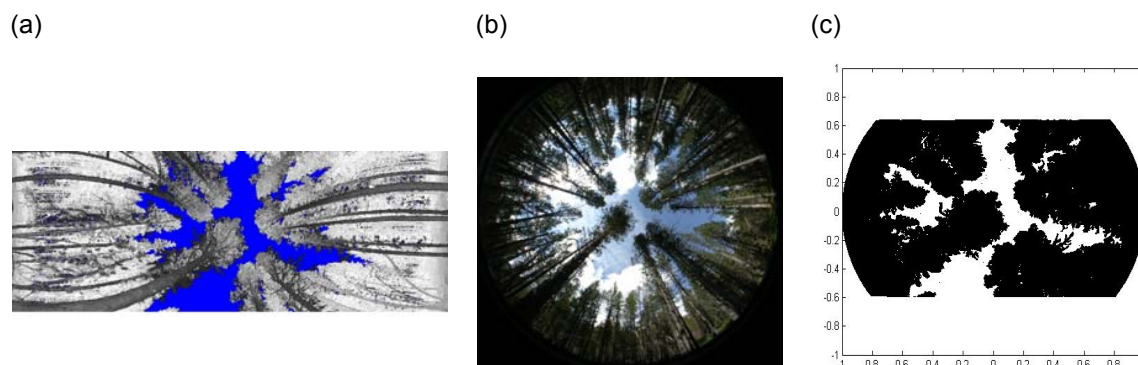


Figure 2. (a) Terrestrial laser scanner data of forest stand displaying intensity of returns in a cylindrical projection. Scan range 180x80 degrees (site 7). (b) Digital hemispherical photograph at same location as figure 5. Equiangular projection. (c) Processed x,y,z coordinate laser scanner data of location in figure 3 showing projection of laser hits onto a hemisphere of unit radius.

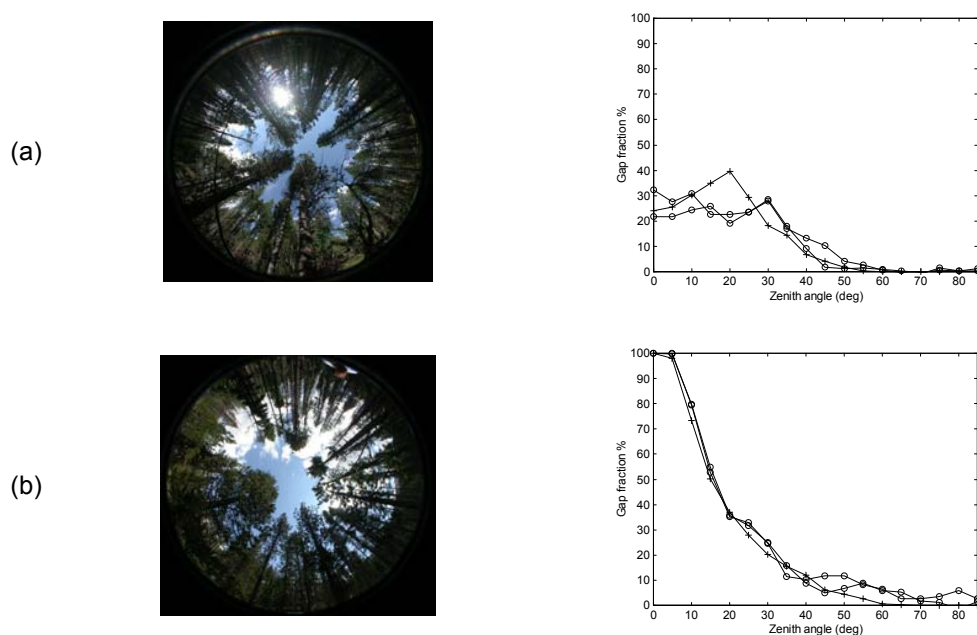


Figure 3. Comparison of gap distribution derived from hemispherical photographs (solid line) and two orthogonal laser scan (broken line). The orthogonal scan sample the same part of the canopy up to a zenith angle of 40o.

## 10 DISCUSSION

The results of this experiment confirm the potential of TLS for measuring the 3d structure of forest canopies. The fit of the hemispherical photography gap fraction data to the TLS gap fraction data was

close for all the measured plots and we are now comparing LAI estimates from the two data sources. However, further work is required to understand the effects of beam divergence on gap detection. At a range of 10m the laser spot size is approximately 30mm in diameter and at 20m it is 60mm. The detectability of gaps with the TLS is therefore range dependent. Further experiments are also required to assess the effect of variation in angular sampling resolution since this is independent of beam divergence.

## 11 CONCLUSIONS

To date the only technique available for creating a permanent record of forest canopy structure is of hemispherical photography. There are a number of key advantages of hemispherical photography over light interception measurements (Jonckheere et al. 2004) but the weaknesses of the photographic approach are the requirement for manual intervention in post-processing the images, and the variability of the measurements with different sky conditions. In contrast, the TLS post-processing routines applied in this research could be automated, and sky conditions had little influence on the quality of the data collected. These factors, coupled with the additional 3d information that can be extracted from the data suggest that TLS will be central to future developments in the measurement of 3d vegetation canopy structure.

## ACKNOWLEDGEMENT

This research was partly funded by EU Spread Contract number EVG1-CT-2001-00043.

## REFERENCES

- Heritage, G.L. and Hetherington, D. (2005) The use of high resolution field laser scanning for mapping surface topography in fluvial systems. *Int. Assoc. of Hydrol. Sci.*, 291, 269-277.
- Hopkinson, C., Chasmer, L., Young-Pow, C. and Treitz, P. (2004) Assessing forest metrics with a ground-based scanning lidar. *Canadian Journal of Forest Research*, 34, 573-583.
- Jonckheere, I., Fleck, S., Nackaerts, K., Muys, B., Coppin, P., Weiss, M. and Baret, F. (2004) Review of methods for in situ leaf area index determination - Part I. Theories, sensors and hemispherical photography *Agricultural And Forest Meteorology*, 121, 19-35.
- Lovell, J.L., Jupp, D.L.B., Culvenor, D.S., Coops, N.C. (2003) Using airborne and ground-based ranging lidar to measure canopy structure in Australian forests, *Canadian Journal of Remote Sensing*, 29, 607-622.
- Thies, M., Pfeifer, N., Winterhalder, D., Gorte, B.G.H. (2004) Three-dimensional reconstruction of stems for assessment of taper, sweep and lean based on laser scanning of standing trees, *Scandinavian Journal of Forest Research*, 19, 571-581.
- Watt, P.J., and Donoghue, D.N.M. (2005) Measuring forest structure with terrestrial laser scanning, *International Journal of Remote Sensing*, 26, 1437-12446.
- Warren-Wilson, J. (1963) Estimation of foliage denseness and foliage angle by inclined point quadrats. *Australian Journal of Botany*, 11, 95-105.
- Weiss, M., Baret, F., Smith, G.J., Jonckheere, I. and Coppin, P. (2004) Review of methods for in situ leaf area index (LAI) determination Part II. Estimation of LAI, errors and sampling. *Agricultural and Forest Meteorology*, 121, 37-53.